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Publication Date

2020-11-01

DOI

10.1016/j.scitotenv.2020.140797

Peer reviewed

Science of the Total Environment 743 (2020) 140797

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Integrated virtual water trade management considering self-sufficient production of strategic agricultural and industrial products

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HIGHLIGHTS

- Integrated virtual water trade management of agriculture and industry
- Maximizing economic revenue and minimizing virtual water consumption
- Optimization by NSGA-II algorithm
- Providing economic and food security by self-sufficiency constraint for internal production
- 40 billion of cubic meters could be saved by importing wheat

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 28 April 2020
Received in revised form 12 June 2020
Accepted 5 July 2020
Available online 7 July 2020

Editor: Ashantha Goonetilleke

Keywords:
Integrated virtual water trade management
Security of production
Agricultural products
Industrial products
NSGA-II

ABSTRACT

The uneven distribution of water on earth causes its scarcity in many countries, hindering economic and human development. Virtual water trading takes place by the export and import of agricultural and industrial products whose production involves water and, so, is one of the methods to cope with water scarcity. This work investigates the integrated management of the virtual water trade of strategic agricultural and industrial products with the goals of maximizing economic revenue and minimizing the consumption of virtual water. Bi-objective optimization is performed with the non-dominated sorting genetic algorithm (NSGA)-II algorithm under two scenarios. One of the scenarios applies production constraints to ensure a minimum of internal or domestic production of agricultural and industrial goods, thus providing a degree of self-sufficiency. This paper applies its methodology to Iran and establishes that the imports of industrial products should be terminated and exports of these products should increase. The results show that the export amount of iron ore increases by 71% due to the application of the self-sufficiency constraint, which shows the profitability of this product in addition to its low water consumption. This paper demonstrates that the optimal solutions for agricultural products (except for potatoes and tomatoes) is achieved by producing at least 50% of the domestic demand, but rarely calls for a higher level of production. This work illustrates through the case study that it is possible to increase economic revenue under water scarcity by proper management of the virtual water trade.

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https://doi.org/10.1016/j.scitotenv.2020.140797
0048-9697/

1. Introduction

The distribution of water resources on earth is such that 97% of all water resources are composed of oceans, which are inherently saline, and the remaining 3% are freshwater, of which more than 69% are glaciers. In spite of the relative scarcity of fresh water, it can meet human demands, but factors such as inadequate management of water resources, inadequate technology development, population growth, and uneven temporal and spatial distribution of water resources on earth raise challenges to achieving sustainable use of water resources. For these reasons, several countries have faced a water-scarcity crisis (Jahandideh-Tehrani et al., 2015). The scarcity of water resources can be a limiting factor for development, which makes the need for optimal utilization of this vital resource more urgent to overcome socio-economic underdevelopment (Sartori et al., 2017; Miglietta et al., 2018).

Optimal management of water resources must take into account economic, social, political, and engineering issues. There are complexities besetting, such as optimal management that are best overcome by optimization methods (Bozorg-Haddad et al., 2009; Fallah-Mehdipour et al., 2014). Optimization models have been categorized as (1) Classical (e.g., linear programming, non-linear programming and etc.) and (2) Evolutionary and meta-heuristic models (e.g., genetic algorithm (GA), honey-bees mating optimization (HBMO), non-dominated sorting genetic algorithm (NSGA) and others) (East and Hall, 1994; Carlisle and Dozier, 2001; Soltanjalili et al., 2011; Sabbaghpour et al., 2012; Abdelaziz et al., 2016). NSGA-II is implemented in this study. It is a widely used algorithm in multi-objective water resources studies (Atiquzzaman et al., 2006; Artina et al., 2012; Aboutalebi et al., 2015, 2016). Optimization with the NSGA-II algorithm produces a set of non-dominated solutions or Pareto fronts. Choosing among the non-dominated solutions must be resolved with conflict-resolution methods such as Nash bargaining (Beygi et al., 2014).

Kerachian and Karamouz (2007) applied the Nash Bargaining method to settle the conflict between water supply with prescribed water quality, supplying multiple water demands, and waste load allocation in a river. Madani (2011) implemented Nash's model as cooperative game theory to illustrate how parties may use environmental and water resources and share the benefits of cooperation under climate change.

Water resources managers must solve water scarcity and search for strategies such as consumption pattern modification, water conservation, water reuse (Loáiciga, 2015), expansion of the water resource sources, and virtual water trade development (Cazcarro et al., 2016; Ridoutt et al., 2018; Fan et al., 2019). The term virtual water was introduced by Allan (1993). Virtual water is the volume of water consumed in the production of an amount of product (whether commodities, agricultural products, or even services) in all the stages of the production chain, from start to finish (Allan, 1993). Hoekstra (2003) introduced a more comprehensive definition of virtual water by positing that virtual water is the volume of water needed to produce an amount of product, depending on climatic conditions, location, production time, and efficiency. According to the later definition, factors such as climatic conditions, place and time of production, management, and planning, and culture influence the virtual water, which varies from product to product across regions (Hoekstra, 2011). It is worth noting the virtual water concept is not limited to agricultural products, and it applies to industrial products and the rendering of services, also.

The importing and exporting of agricultural and industrial products involve water in virtual form. Therefore, virtual water trade is receiving increasing attention in water resources management nowadays. Virtual water trade has been studied from several perspectives, such as the virtual water trade between regions (e.g., Sun et al., 2016; Chouchane et al., 2017; Wahba et al., 2018; Bae and Dall'erba, 2018; Ridoutt et al., 2018), food crisis and security (Tamea et al., 2016), and risk assessment of trade (Qu et al., 2017), where the input-output analysis is implemented. Hoekstra and Hung (2002) quantified the flow of virtual water trade between nations in the context of international trade of crops during the period 1995–1999. Their evaluations showed that 13% of the water consumed for the production of products in the world is not used for domestic consumption but is exported in virtual form. Mohammadi-Kanigolzar et al. (2014) reported a study of virtual water flow in Iran for the period 2001–2008, demonstrating that Iran has a water-import dependency. Some of the goods that require relatively small inputs of water and have high economic efficiency are imported, while some products with relatively high virtual water consumption are exported in large amounts. Jiang et al. (2015) applied a multi-regional input-output model in China and determined that some provinces, despite their very poor water resources, are among the first exporters of virtual water. Other provinces are heavily dependent on products imported (imported virtual water). The latter authors proposed a market-based pricing system and the application of new technologies to increase water-use efficiency.

Zhang et al. (2016) evaluated China's virtual water trade in the years 2001–2013. Sun et al. (2016) calculated China's virtual water trade through grain and cereal trade. The latter authors recommended that China focuses on water-saving policies and boosting its water use efficiency to prevent future food crises. Najafi Alamdarlo et al. (2018) investigated the pattern of virtual water trade flow in Iran. Their results revealed that the wheat production policy of Iran will increase pressure on its water resources. Wahba et al. (2018) examined the impact of virtual water trade and domestic use on available water sources by means of an input-output method. They chose Egypt as a case study and calculated imports, exports, and estimated household water consumption. Qian et al. (2018) applied two input-output methods and structural analysis for assessing the potential for socioeconomic development in relation to water sustainability in Yunnan, China. Wang et al. (2019) examined the flow of virtual water from grain and cereal trade in China. They concluded that such trade has reduced water-use efficiency in China.

The majority of virtual water studies have focused on monitoring the virtual water trade between countries but never demonstrated the optimal pattern of this trade, which could lead to significant water savings. Also, published works reveal numerous studies on virtual water trade in which the agricultural and industrial sectors are vetted individually. Ample evidence supports the approach of assessing jointly the agricultural and industrial sectors for developing a comprehensive understanding of water consumption and their roles in the virtual water trade (Đokić and Jović, 2017). Therefore, this work introduces bi-objective optimized management of virtual water trade in the agricultural and industrial sectors considering food and production security. The Nash Bargaining method is implemented to the Pareto front solutions to achieve a Nash equilibrium solution for virtual water trade. Iran is chosen as a case study for this paper's methodology, which could raise economic revenue while reducing virtual water consumption.

2. Methods

This section introduces a methodology to optimize the virtual water trade of the industrial and agricultural sectors with the objectives of maximizing net revenue and minimizing virtual water use implementing the Non-Dominated Sorting Genetic Algorithm (NSGA)-II optimization method under two scenarios. The first and second scenarios optimize virtual water without and with a self-sufficiency constraint, respectively. The self-sufficiency constraint requires that 50% of a country's demand for strategic products be internally or domestically produced. The Nash bargaining method is applied to the Pareto fronts calculated for the two scenarios to determine their Nash equilibrium solutions. This paper's methodology (see flowchart in Fig. 1) is illustrated with conditions and data in Iran corresponding to 2018.

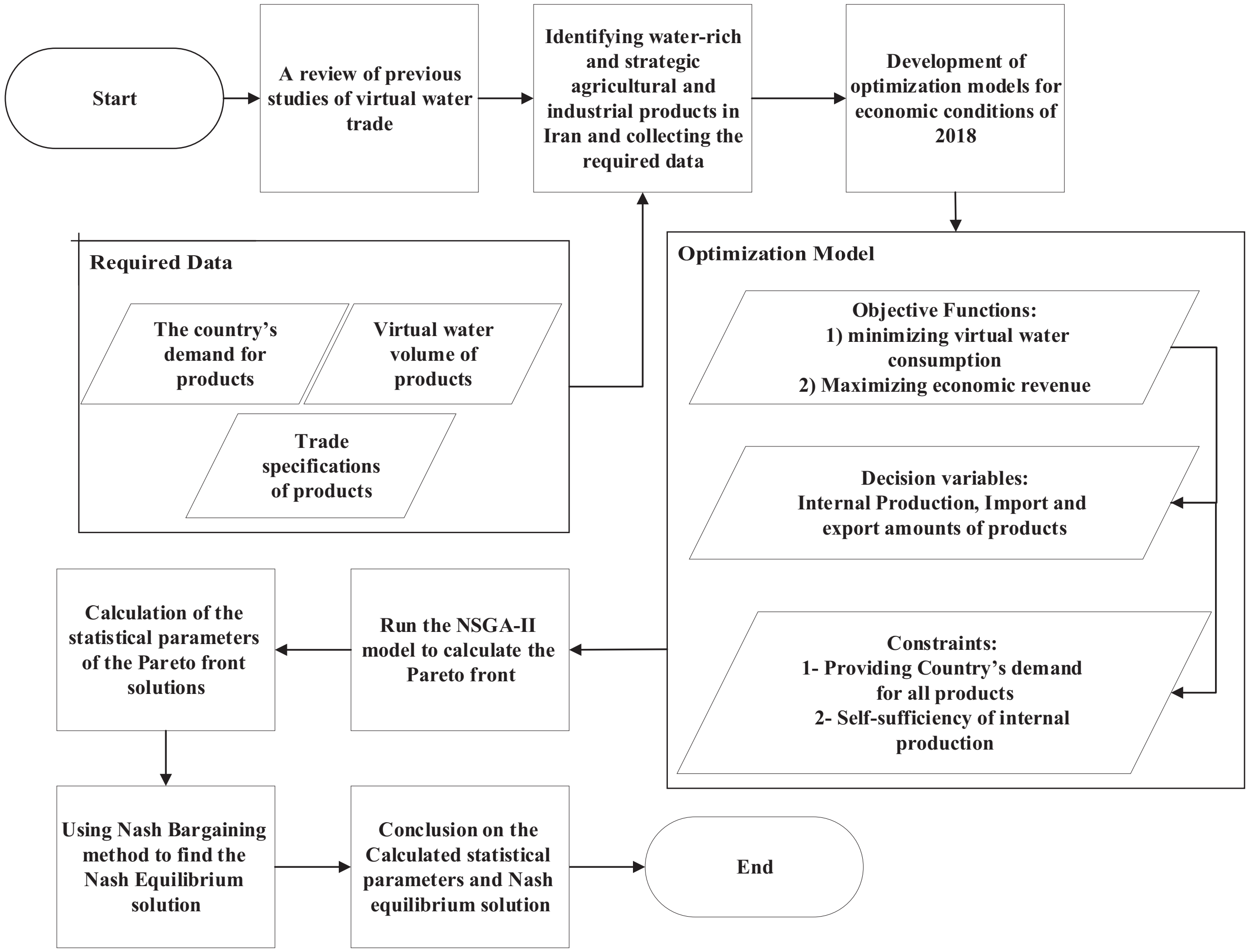

Fig. 1. Methodology's flowchart.

2.1. Optimization models

This work's objectives are minimizing the virtual water involved in the trade of products, and maximizing the net revenue from traded products by using the NSGA-II algorithm (Reed et al., 2003; Tang et al., 2007). The decision variables of the stated objectives are the amounts of imported and exported products. In the following, the optimization models are explained.

2.1.1. Minimization of the virtual water use

The first objective minimizes virtual water use, as expressed by Eq. (1):

$$Minimize.\sum_{i=1}^{m} VWC_iC_i + \sum_{j=1}^{n} VWS_jS_j + \sum_{u=1}^{O}\sum_{K=1}^{P} VWC_UEC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} VWS_LES_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} VWC_UIC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} VWS_LIS_{LK} \quad (1)$$

in which, C_i= the amount of domestic consumption of the domestic agricultural product i (metric tons, 1 metric ton = 1000 kg), m= the number of agricultural products, S_j= the amount of domestic consumption of the domestic industrial product j (tons), n= the number of industrial products, IC_{UK}= the amount of crop U imports from the country K (tons), p= the number of countries which have trade relations with the under-studied country, IS_{LK}= the amount of industrial product L imports from the country K (tons), O= number of traded agricultural products. EC_{UK}= the amount of domestic agricultural product U exported to country K (tons), G= number of traded industrial products. ES_{LK}= the amount of domestic industrial product L exported to country K (tons), VWC_i= virtual water consumption of Crop i, and VWS_j= virtual water consumption of industrial product j.

2.1.2. Maximization of economic revenue

The second objective is to maximize net revenue from the trade of products consuming virtual water:

$$Maximize.\sum_{i=1}^{m} B_iC_i + \sum_{j=1}^{n} b_jS_j + \sum_{U=1}^{O}\sum_{K=1}^{P} R_{UK}EC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} r_{LK}ES_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} G_{UK}IC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} g_{LK}IS_{LK} \quad (2)$$

in which, B_i= net revenue from the sale of agricultural product i in the country under study (million dollars), b_j= net revenue from the sale of industrial product j in the country under study (million dollars), R_{UK}= net revenue of one unit of agricultural product U exported to country K (million dollars), r_{LK}= net revenue of one unit of industrial product L exported to country K (million dollars), G_{UK}= cost of one unit of agricultural product U imported from country K (million dollars), g_{LK}= cost of one unit of industrial product L imported from country K (million dollars), The following constraints apply in the optimization model:

- Providing the country's demands of all considered products

$$\sum_{i=1}^{m} C_i + \sum_{j=1}^{n} S_j + \sum_{U=1}^{O}\sum_{K=1}^{P} IC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} IS_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} EC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} ES_{LK} \geq \sum_{i=1}^{m} DC_i + \sum_{j=1}^{n} DS_j \tag{3}$$

in which, DC_i= the country's demand of agricultural product i (tons), and DS_j= the country's demand of industrial product j (tons).

- The net revenue from products' sale must be greater than the costs of imports in the year under study

$$\sum_{i=1}^{m} B_i C_i + \sum_{j=1}^{n} b_j S_j + \sum_{U=1}^{O}\sum_{K=1}^{P} R_{UK} EC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} r_{LK} ES_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} G_{UK} IC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} g_{LK} IS_{LK} \geq A \tag{4}$$

in which,A= the required net revenue accruing from the sale of agricultural and industrial products in the country and from the sale of exported products minus the cost of importing the products under consideration in the year in question (million dollars).

- Self-sufficiency

Countries' trade policies change and various restrictions affect the exchange between countries. Therefore, it may be necessary for countries to produce a significant share of products consumed. This work introduces a self-sufficiency constraint which compels the country to produce at least 50% of all the considered products' domestic demand. The cited percent can be changed to best reflect a country's specific conditions, and in some cases satisfaction of the internal demand of some products by importation may be economically justified. This work applies the 50% self-sufficiency constraint under Scenario 2 only:

Self-sufficiency of agricultural and industrial products expressed respectively by Eqs. (5) and (6):

$$\sum_{i=1}^{m} C_i \geq \frac{\sum_{i=1}^{m} DC_i}{2} \tag{5}$$

$$\sum_{j=1}^{n} S_j \geq \frac{\sum_{j=1}^{n} DS_j}{2} \tag{6}$$

- The virtual water used in production must be less than the virtual water available in the year under review

$$\sum_{i=1}^{m} VWC_i.C_i + \sum_{j=1}^{n} VWS_j.S_j + \sum_{U=1}^{O}\sum_{K=1}^{P} VWC_{UK}.EC_{UK} + \sum_{L=1}^{G}\sum_{K=1}^{P} VWS_{LK}.ES_{LK} - \sum_{U=1}^{O}\sum_{K=1}^{P} VWC_{UK}.IC_{UK} - \sum_{L=1}^{G}\sum_{K=1}^{P} VWS_{LK}.IS_{LK} \leq H \tag{7}$$

in which H= the volume of virtual water available in the year under study, which equals the sum of the agricultural and industrial virtual water uses (cubic meters). Under sustainable water use H guarantees the sustainability of a country's water resources.

The main purpose of multi-objective optimization is to obtain a set of non-dominated solutions allowing the decision maker to choose the preferred combination of decision variables among those calculated in a Pareto front. Evolutionary algorithms such as NSGA-II (Deb and Zitzler, 2001) calculate a set of non-dominated or Pareto sets from which to choose a preferred solution.

2.2. The Nash bargaining method

A set of non-dominated solutions are available at the end of the optimization from which the preferred solution is chosen using conflict-resolution methods. There are several conflict resolution methods, including multi-criteria decision-making models and game theory-based models. This work applies the Nash bargaining method from game theory-based models.

The Nash bargaining method is a conflict-resolution method pioneered by John Nash (1950) on the basis of game theory. This method applies a utility function to each player participating in a game. The utility functions measure how satisfied each player is with the achievement of a goal. Obviously, the higher the player's achievement of a goal, the higher the utility derived, and vice versa. Let the utility function of player i be represented by u_i and$S = \{u_1, u_2, u_3, ..., u_N\}$ denote the N-dimensional set of utility functions. Each element in the set represents a solution to the conflict-resolution problem. In addition to the set points of S there is a point which is referred to as the point of disagreement (d), which measures the degree of disagreement on the part of a player with respect to a solution associated with this point (H_d). In Nash bargaining the goal is to find a point on the set S that is the most distant from d. The regular pair (S, d) represents the set position where all the elements of the set S are larger than d (Ganji et al., 2007).

In general, numbers between zero and one are used to represent utility functions. The best value of a target function (regardless of minimization or maximization) is assigned a value of 1 and the lowest value of 0. In this case all stakeholders have a utility between zero and one providing a normalized range of values for comparison purposes. The purpose of Nash bargaining is to maximize Eq. (8).

$$Max. \prod_{i=1}^{N} (u_i - d_i) \tag{8}$$

in which, N= the number of players and d_i= disagreement point for player i. In summary, the goal of the Nash bargaining method is to select a solution where all players are at a maximum distance from the point of disagreement. The disagreement point d when maximizing economic revenue and minimizing virtual water use represents the 2018 revenue and virtual water use.

3. Case study

This work implements the methodology presented above to Iran's international trade in strategic agricultural and industrial products. Iran is located in Southeastern Asia in the Middle East region, with an area of 1,648,195 km^2 and 31 provinces. It is bordered by Azerbaijan, Armenia, and Turkmenistan to the north, Afghanistan, and Pakistan to the east, and Turkey and Iraq to the west. It is also bounded on the north by the Caspian Sea and on the south by the Persian Gulf and the Oman Sea. Agricultural and industrial products trade in Iran accounts for a large portion of the country's annual economic income as well as for its consumption of water resources.

Iran is one of the countries where agriculture was first practiced. Due to poor soil and poor water distribution, only 12% of Iran's agricultural land (including gardens, vineyards, etc.) is cultivated. Agriculture accounts for about 92% of the country's water use. This work considers six strategic agricultural products (wheat, barley, rice, date, potatoes, and tomatoes) (Table 1). Strategic agricultural products feature the following traits: (a) high virtual water consumption, (b) high trading activity (import and export), which leads to high water consumption

Table 1
Characteristics of products.

	Specifications	Internal production	Internal sale price	Export	Export price	Import	Import price	Virtual water
	Unit	10^3 tons	Dollar/tons	10^3 tons	Dollar/tons	10^3 tons	Dollar/tons	m^3/tons
Products	Wheat	13,300	153	440	255	74	279	3184
	Rice	3106	1329	0	2538	1294	938	3531
	Barley	3102	147	0	750	2673	194	1534
	Date	1223	1617	256	982	0	982	2685
	Potato	5143	183	551	506	1	1664	326
	Tomato	5667	287	691	509	0	509	349
	Steel	21,884	2162	8616	395	2894	737	28
	Iron ore	39,540	121	247	420	0	97	4
	Aluminum	351	878	175	1770	153	1075	88
	Copper	160	2733	101	1953	29	6666	14
	Cement	54,720	12	12,300	33	19	1685	74

and high economic revenue or cost. The same traits apply to industrial products. There are many active industries in Iran, including petrochemical, steel, cement, and others. These industries, despite their high profitability, have a significant share of the country's water resources consumption. The industrial products considered in this study are steel, iron ore, aluminum, copper, and cement (Table 1). The agricultural and industrial data were provided by Iran's Ministry of Agriculture and the Ministry of Industry, Mining and Trade, respectively.

4. Results and discussion

This paper's optimization methodology finds a set of optimal solutions for maximizing revenue and minimizing virtual water consumption under two scenarios by implementing the NSGA-II algorithm. The self-sufficiency constraint is not applied under the first scenario, which means that some products can be imported to meet the country's whole demand. The second scenario, on the other hand, imposes the self-sufficiency constraint, which means that under this scenario, domestic production provides at least 50% of the country's demand for products. The Nash Bargaining Method is applied to find the Nash equilibrium solution from the NSGA II-derived Pareto fronts.

Table 1 shows the year 2018 statistics for agricultural and industrial trade. It is seen in Table 1 that wheat has the largest share of virtual water use among all the agricultural products. Importing all the domestic demand would save about 40 (10^9 m^3) of water. Also, multiplying the export amount by the virtual water, indicates that dates and tomatoes have the largest virtual water exports equal to 687 and 241 (10^6 m^3), respectively. Concerning industrial products, the largest share of virtual water trade corresponds to cement, in the amount of 4 billion cubic meters of water annually. The second largest volume of virtual water export corresponds to steel, which equals 241 (10^6 m^3).

4.1. Scenario 1

This scenario does not impose a self-sufficiency constraint, thus allowing imports to meet all the country's demands for products. The Pareto front of this optimization is shown in Fig. 2(a), which also depicts the Nash equilibrium point and two global solutions of two single-objective optimizations (maximizing economic income and minimizing virtual water use), which were calculated with the LINGO software.

The case of optimization with the single objective of minimizing virtual water consumption has a global optimum, which is about 1% different and of better quality than the corresponding boundary or extremal point on the Pareto front. The case of optimization with the objective of maximizing net revenue produced a global optimum that was 2.9% superior than the corresponding boundary or extremal point of the Pareto front. These results show the NSGA-II model optimizes the virtual water trade, accurately.

Point (0,0) in Fig. 2(a) shows the status of water consumption and economic income in the year 2018. Thus, negative numbers on the horizontal axis represent less use of virtual water, and positive numbers represent more consumption of virtual water than in 2018. Negative numbers on the vertical axis represent less net revenue, and positive numbers represent more net revenue than in 2018. Therefore, there are acceptable and unacceptable solutions on the Pareto front of Fig. 2 (a). In the first category are solutions which have higher economic income and lower virtual water use than in 2018. The unacceptable

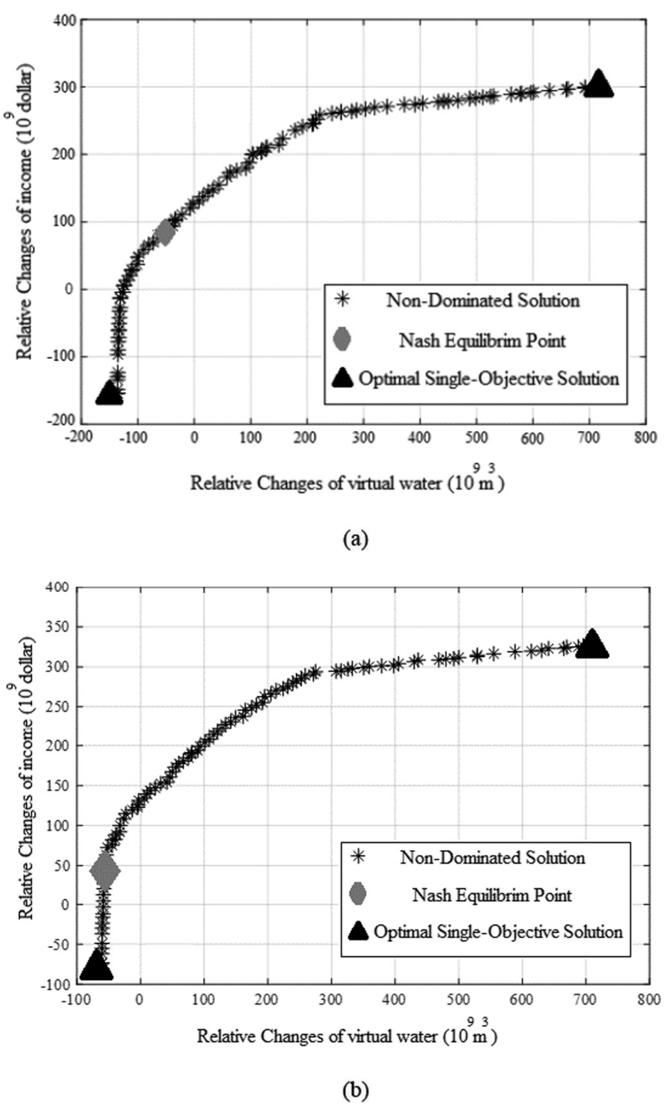

Fig. 2. The set of non-dominated solutions, Nash equilibrium point, and optimal single-objective solutions under (a) Scenario 1 and (b) Scenario 2.

features are of two kinds. Among the first kind are solutions that had lower virtual water consumption and lower income than in 2018. Among the second kind are solutions that had a higher income and higher virtual water than in 2018. The Nash bargaining method was applied in the acceptable region of solutions producing the Nash equilibrium point with relative savings in water consumption equal to 34.64 (10^9 m^3) and a rise in revenue equal to 74.82 (10^9 Dollars).

It is seen in Fig. 3(a) that wheat's demand is met by importing this crop according to the Nash equilibrium solution. Concerning rice, however, the situation is different, and in addition to supplying the country's demand for domestic production, it exhibits high levels of export. Barley and dates have no exports, and more than 50% of the country's demand for both crops is met by imports. Also, due to the high prices of tomatoes and potatoes compared to their virtual water consumption, they exhibit high exports in addition to supplying the country's demands.

It is also seen in Fig. 3(b) that industrial products produced domestically meet all the country's demands in the Nash equilibrium solution. Exporting industrial products is significant in the country's total economic revenue because of their high price relative to the consumed water. The largest share in the virtual water trade of industrial products concerns cement, involving about 4 billion cubic meters of water annually. Cement has the largest share of total water consumption in the industrial sector. All the country's demand for cement is met by internal production, and exports account for about 40% of total production. There are no steel imports, and all the country's demands are met by internal or domestic production. Also, the amount of steel exports is the second largest among industrial products. Concerning aluminum and copper products, the country's need is fully met by domestic production. The country's demand for iron ore is also met by internal production, which also supports exports.

According to Table 2, wheat demand would be best met by imports. The rice demand is fully met by internal production, and the export of this product accounts for more than 50% of production. Barley demand is 95% met by imports. Imports of dates are necessary to meet the country's demand in conjunction with internal production. Potato and tomato exports account for 89% and 87% of their production, respectively.

Table 3 shows internal production meets the country's demand for industrial products. Overall, exports in the industrial sector account for a significant portion of production, and the production and export products such as cement with high water consumption and high economic value enhances their attractiveness as a matter of national priorities.

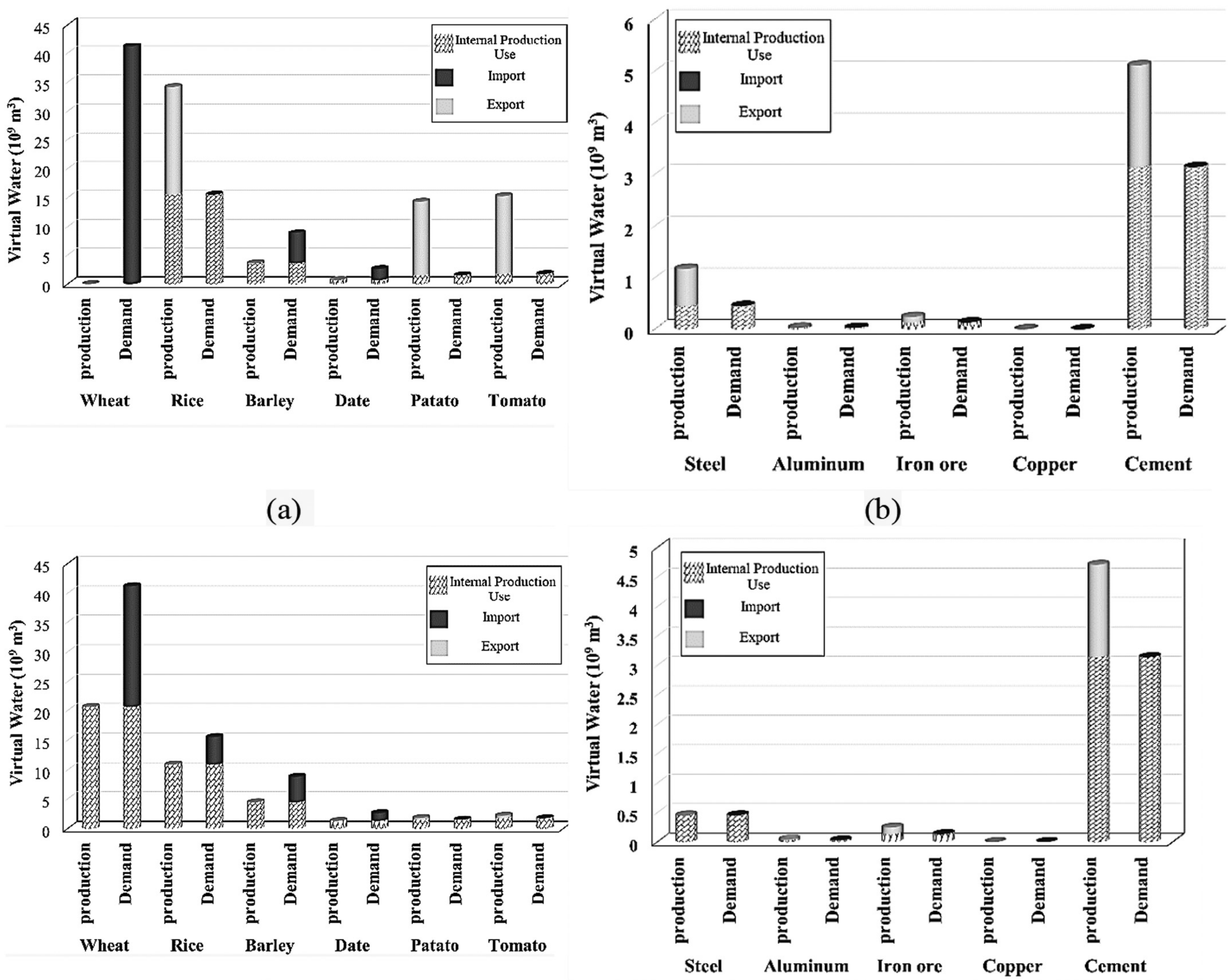

Fig. 3. Comparison of virtual water use corresponding to (a) agricultural products, (b) industrial products under Scenario 1, (c) agricultural products, (d) industrial products under Scenario 2. All graphs correspond to the Nash equilibrium solution.

Table 2
Statistical parameters of acceptable solutions for agricultural products under Scenario 1 (no self-sufficiency constraint imposed).

Product		Parameter			
		Average (10^3 tons)	Median (10^3 tons)	Minimum (10^3 tons)	Maximum (10^3 tons)
Wheat	Import	12,605	12,809	10,728	12,934
	Export	0	0	0	0
	Use of internal production	99	91	0	213
Rice	Import	0	0	0	0
	Export	4860	4580	0	8963
	Use of internal production	4400	4400	4400	4400
Barley	Import	5658	5774	3027	5774
	Export	0	0	0	0
	Use of internal production	1993	2257	1	2748
Date	Import	677	697	597	961
	Export	0	0	0	0
	Use of internal production	183	199	6	370
Potato	Import	0	0	0	0
	Export	38,736	40,657	30,838	43,647
	Use of internal production	4592	4592	4592	4592
Tomato	Import	0	0	0	0
	Export	33,359	39,366	3336	45,046
	Use of internal production	4976	4976	4976	4976

4.2. Scenario 2

This scenario applies the self-sufficiency constraint in the model, requiring the country to produce at least 50% of all demands for products. The Pareto front of this optimization is shown in Fig. 2(b), which also depicts the Nash equilibrium point and two global solutions of two single-objective optimizations (maximizing economic income and minimizing virtual water use), which were calculated with the LINGO software.

Optimization with the objective of minimizing virtual water consumption yielded a global optimum that was about 1.5% different and superior in quality than the corresponding boundary or extremal point on the Pareto front. Optimization with the objective of maximizing revenue yielded a global optimal point that was 1.46% different and of better quality than the corresponding or extremal point on the Pareto front, which shows the NSGA-II model optimizes the virtual water trade with high accuracy.

The acceptable solutions of this Pareto front are those with higher economic revenue less virtual water consumption than in 2018 [or point (0,0)]. The Nash bargaining method was applied to the acceptable solutions on the Pareto front, and the Nash equilibrium point has a relative savings in water consumption of 45.10 (10^9 m^3) and an increase in revenue equal to 48.65 (10^9 Dollars).

It is shown in Fig. 3(c) that internal agricultural production provides at least 50% of the country's crop demands in the Nash equilibrium solution. Wheat, rice, barley, and date crops exhibit imports and internal production. Tomato and potato crops produced internally fully satisfy the country's demands. 19% and 16% of the tomato and potato crops productions were exported, respectively.

With respect to the industrial products group, it is seen in Fig. 3(d) that all the country's needs for products are met through internal production; thus, imports were nil for all products. In the export sector, steel's exports account for less than 1% of production, but exports of aluminum, iron ore, copper and cement account for 33, 45, 21, and 33% of production, respectively.

Table 4 shows that, on average, between 45% and 49% of the demands of wheat, rice, barley, and dates are supplied by imports. Therefore, the best possible solutions are those in which internal production provides at least 50% of the country's but seldom do the optimized solutions call for producing more than 50% of studied products. Also, exports of potatoes and tomatoes accounted for 74% and 77% of production, respectively. It is seen in Table 5 that there were no imports of industrial products. The exports of steel and iron ore, unlike those of aluminum, copper, and cement, exceeded their internal consumption.

It is evident from Fig. 3(a) and (c) that with the application of the self-sufficiency constraint, the internal production of agricultural products in the Nash equilibrium solution increases so that at least half of the country's demand for these products is met by domestic production. It is also observed that the model proposes the production of wheat, barley, and dates up to 50% of the domestic demand, and rarely exceeds that amount. Exports of tomatoes and potatoes also decrease compared to scenario 1. Concerning industrial products, according to Fig. 3(b) and

Table 3
Statistical parameters of acceptable solutions for industrial products under Scenario 1.

Product		Parameter			
		Average (10^3 tons)	Median (10^3 tons)	Minimum (10^3 tons)	Maximum (10^3 tons)
Steel	Import	0	0	0	0
	Export	19,342	24,876	0	28,414
	Use of internal production	16,162	16,162	16,162	16,162
Aluminum	Import	0	0	0	0
	Export	124	123	0	294
	Use of internal production	329	329	329	329
Iron ore	Import	0	0	0	0
	Export	27,940	44,090	0	49,080
	Use of internal production	37,113	37,113	37,113	37,113
Copper	Import	0	0	0	0
	Export	99	132	0	207
	Use of internal production	87	87	87	87
Cement	Import	0	0	0	0
	Export	29,116	41,532	0	50,823
	Use of internal production	42,439	42,439	42,439	42,439

Table 4
Statistical parameters of acceptable solutions for agricultural products under Scenario 2 (self-sufficiency constraint imposed).

Product		Parameter			
		Average (10^3 tons)	Median (10^3 tons)	Minimum (10^3 tons)	Maximum (10^3 tons)
Wheat	Import	6290	6245	6373	6464
	Export	0	0	0	0
	Use of internal production	6494	6484	6470	6561
Rice	Import	1884	1626	1014	3262
	Export	0	0	0	0
	Use of internal production	2252	2209	2200	3092
Barley	Import	2935	2963	2433	3077
	Export	0	0	0	0
	Use of internal production	2960	2919	2698	3342
Date	Import	470	472	467	490
	Export	0	0	0	0
	Use of internal production	490	491	477	500
Potato	Import	0	0	0	0
	Export	13,333	2600	0	42,752
	Use of internal production	4592	4592	4592	4592
Tomato	Import	0	0	0	0
	Export	17,106	6378	0	45,483
	Use of internal production	4976	4976	4976	4976

Table 5
Statistical parameters of acceptable solutions for industrial products under Scenario 2.

Product		Parameter			
		Average (10^3 tons)	Median (10^3 tons)	Minimum (10^3 tons)	Maximum (10^3 tons)
Steel	Import	0	0	0	0
	Export	18,626	29,282	0	31,130
	Use of internal production	16,162	16,162	16,162	16,162
Aluminum	Import	0	0	0	0
	Export	71	75	0	165
	Use of internal production	329	329	329	329
Iron ore	Import	0	0	0	0
	Export	48,020	48,557	31,148	49,899
	Use of internal production	37,113	37,113	37,113	37,113
Copper	Import	0	0	0	0
	Export	65	69	23	121
	Use of internal production	87	87	87	87
Cement	Import	0	0	0	0
	Export	3044	2030	0	21,220
	Use of internal production	42,439	42,439	42,439	42,439

(d), the export of steel decreases, and the export of cement and iron ore increases in scenario 2 in comparison to scenario 1 at the Nash equilibrium solution.

According to Tables 2 and 4, on average, wheat production, increased and its import decreases under scenario 2 compared to scenario 1. Rice production also decreases. This means that, on average, its exports have been reduced to zero, and its import equals 1884 (10^3 tons). The production of dates and barley also increases, and their imports are reduced. Exports of potatoes and tomatoes also fell 65% and 49%, respectively. Concerning industrial production, according to Tables 3 and 5, on average, exports of steel, aluminum and copper products do not change much, but the export of iron ore increases by 71% due to the application of the self-sufficiency constraint, which demonstrates the profitability of this product in addition to its low water consumption. Overall, applying the self-sufficiency constraint reduces the production of high virtual-water consumption products, and raises the production of products with high profitability to compensate for the reduction in trade net revenue.

This paper's results show that optimizing trade lowers water consumption and raises revenue. This paper's method provides an accounting of the country's virtual water trade and the range of changes in the trade parameters for each product (import, export, and internal production), which is necessary for decision makers in the planning of agricultural and industrial policies.

5. Concluding remarks

This study integrates the management of virtual water trade in the agricultural and industrial sectors. The objectives of minimizing virtual water consumption and maximizing revenue were considered and modeled with the NSGA-II algorithm under two scenarios. Scenario 2 imposes a self-sufficiency constraint requiring internal production of at least 50% of the domestic demand for all considered products.

The current wheat production policy of Iran would increase pressure on the water resources of the country (Najafi Alamdarlo et al., 2018). Our results show wheat has the largest share of virtual water consumption, and importing wheat to meet the domestic demand would save about 40 (10^9 m^3) of water. In addition, all industrial products' demands should be supplied by internal production without resorting to imports. Also, potato and tomato crops must be produced internally, with large amounts being exported to raise revenue. Applying the self-sufficiency constraint under Scenario 2 reduces the trade revenue compared to Scenario 1, and virtual water saving increases in comparison to Scenario 1. This means that self-sufficiency reduces water use and increases revenue by decreasing agricultural exports and increasing industrial exports. Also, this work demonstrates that the optimal solutions for agricultural products (except for potatoes and tomatoes), are achieved by producing at least 50% of the domestic demand, but the solutions rarely call for larger production levels.

This work's results show that Iran must import more agricultural products and export more industrial products to achieve sustainable water resources management. Some of the products with low water requirements and high economic returns have been preferentially imported, while some products with high virtual water consumption have had relatively high export amounts in Iran (Mohammadi-Kanigolzar et al., 2014). The developed optimization model solves these situations by calling for the increase the export of profitable and low-water consumption products, such as potatoes, tomatoes, and iron ore.

Sustainable use of water resources is a challenge worldwide; yet, sustainability could be achieved by optimizing virtual water trade. Each country can achieve sustainable use of water resources according to their availability. The amount of sustainable water use should be a constraint in input/output modeling of a country's trade and demand for agricultural and industrial products. Considering more products and the uncertainties in their pricing and production would render the optimization solutions more comprehensive. This constitutes a topic of continuing research.

CRediT authorship contribution statement

Mohammad Delpasand: Data curation, Formal analysis, Investigation, Resources, Software, Visualization, Writing - original draft. **Omid Bozorg-Haddad:** Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing - original draft. **Hugo A. Loáiciga:** Validation, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors thank Iran's National Science Foundation (INSF) for its financial support of this research.

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